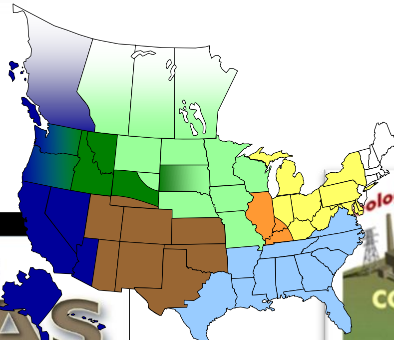
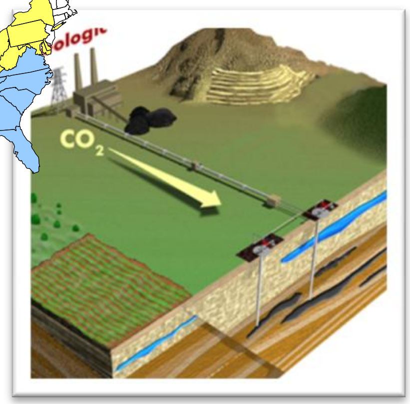
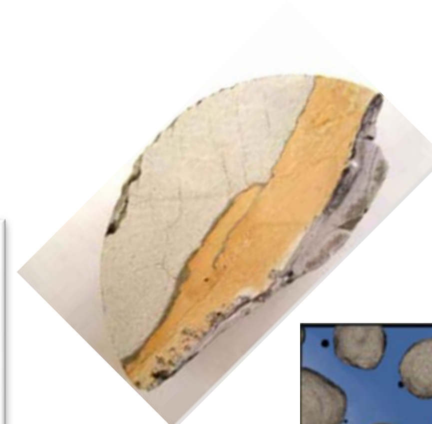
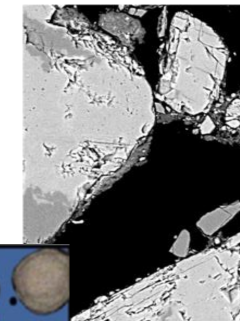
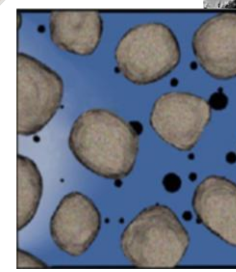








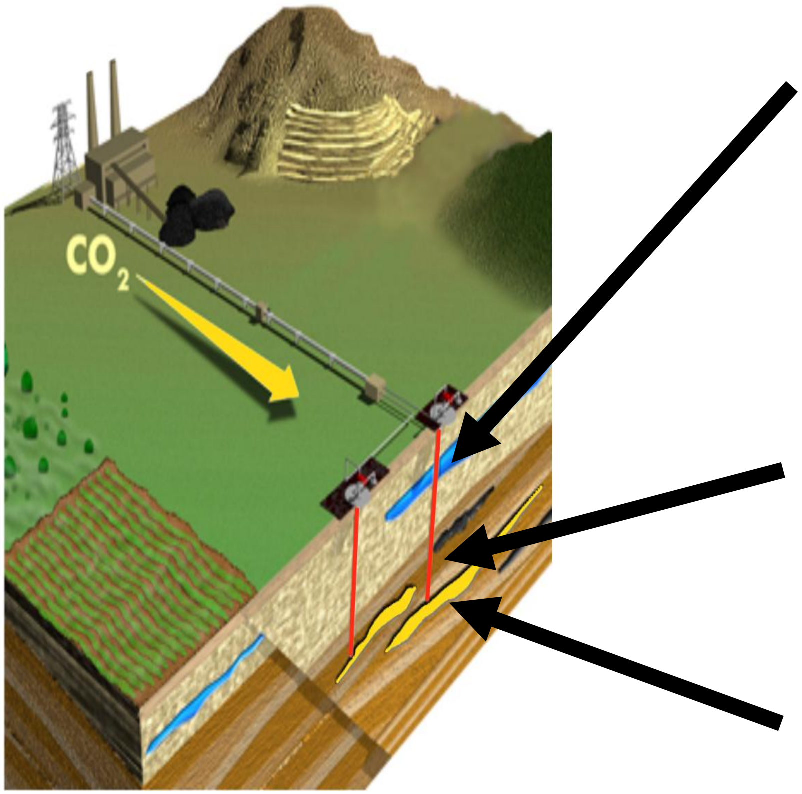


National Risk Assessment Partnership (NRAP):

A Multi-lab Research Initiative for Long-term Stewardship

George Guthrie
Office of Research & Development
National Energy Technology Laboratory

Assessing potential risks for a storage site requires consideration of factors from reservoir to receptor.



Lawrence Berkeley National Lab
Lawrence Livermore National Lab
Los Alamos National Lab
National Energy Technology Lab
Pacific Northwest National Lab

Outside of the Reservoir

- **Strategic monitoring for the site (during injection & post closure)**
- **Potential impacts of CO_2 release**
- **Protection of subsurface resources (groundwater, minerals, etc.)**

Seal

- **Seal characterization**
- **Seal & wellbore integrity**
- **Mitigation strategies**

Reservoir

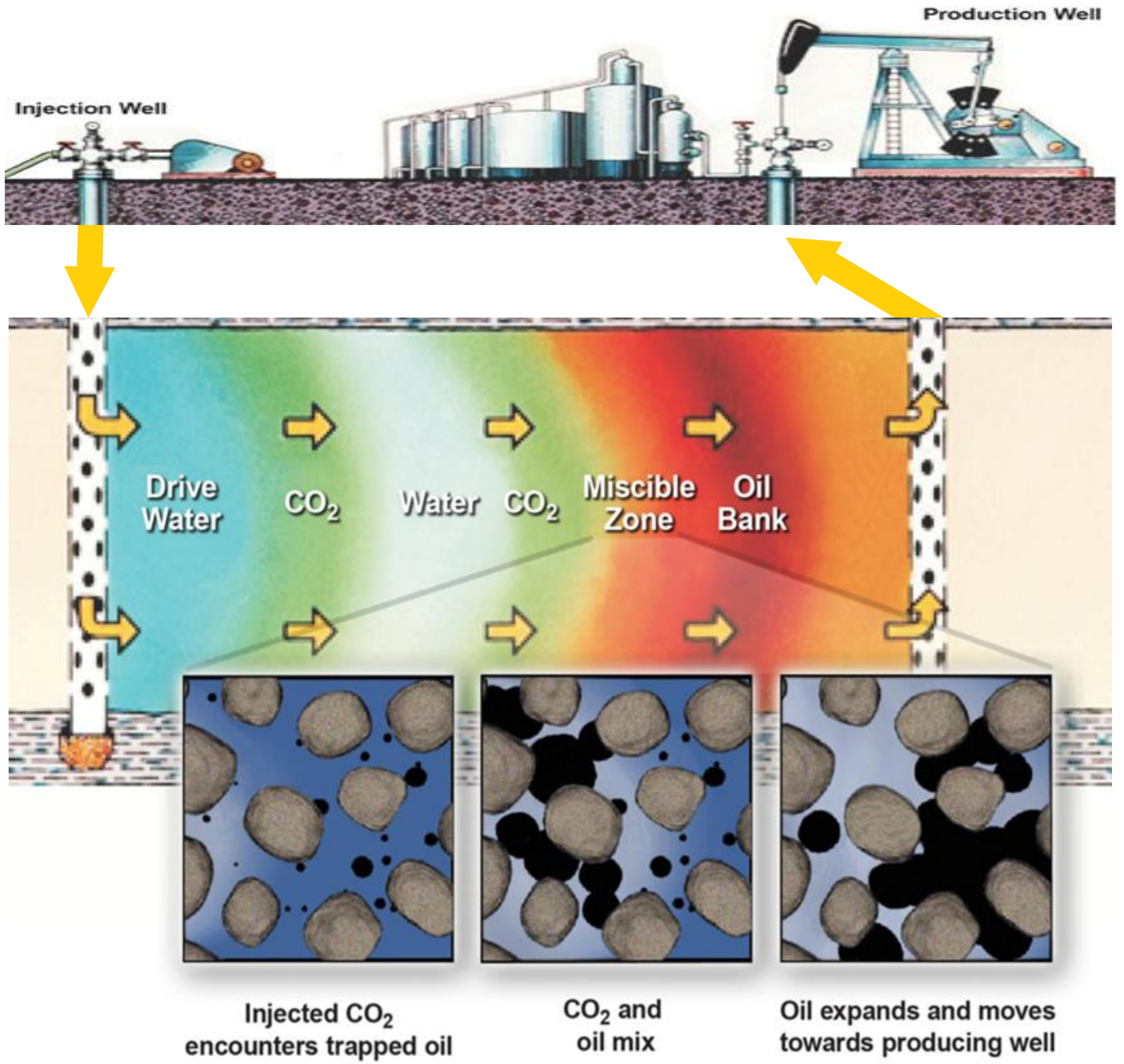
- **Strategic site characterization**
- **Capacity & injectivity over time**
- **Plume movement in reservoir (CO_2, brine, pressure front)**
- **Impacts from introducing CO_2 into the reservoir**

+/–30% Capacity

99% Permanence

Quantitative Risk Assessment

Over decades, CO_2-EOR has developed tools/understanding needed to manage CO_2 injection into geologic reservoirs.



✓ multiphase flow of CO_2, brine, oil during EOR operation

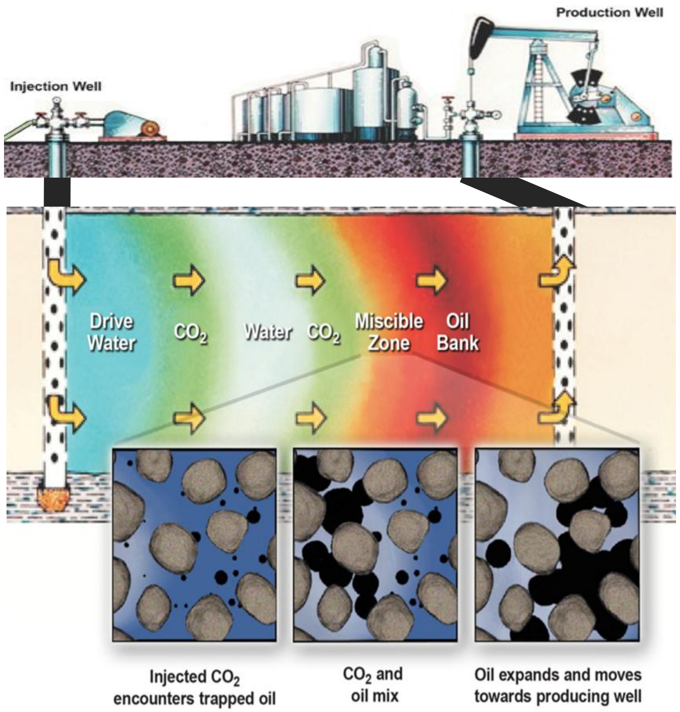
- EOR = injection + production

Figures from US-DOE/NETL 2009 ("Carbon Dioxide Enhanced Oil Recovery: Untapped Domestic Energy Supply and Long Term Carbon Storage Solution")

New (beyond EOR) tools/understanding are needed for CCS.

✓ *multiphase flow of CO_2, brine, oil during EOR operation*

- *EOR = injection + production*



coupled flow–reaction–stress/strain

? *variable flow dynamics*

- *pressure driven regimes vs. buoyancy driven regimes*
- *viscosity of CO_2 < H_2O (fingering)*
- *hydrophobic vs. hydrophyllic minerals*
- *porous flow and fracture flow*

? *site characterization*

- *deeper reservoirs; new environments; need to prove seal*
- *quantification of CO_2 fate*

? *dynamics from reservoir to surface*

- *multiple coupled subsystems*

? *geomechanical behavior coupled to flow*

- *flow-stress are linked through permeability and P*

? *long-term CO_2-water interactions coupled to flow*

- *CO_2 dissolves into water over days (diffusion)*
- *denser CO_2-water develops plumes (advection)*
- *CO_2 mixes in reservoir over $10^{2–3}$ yrs*

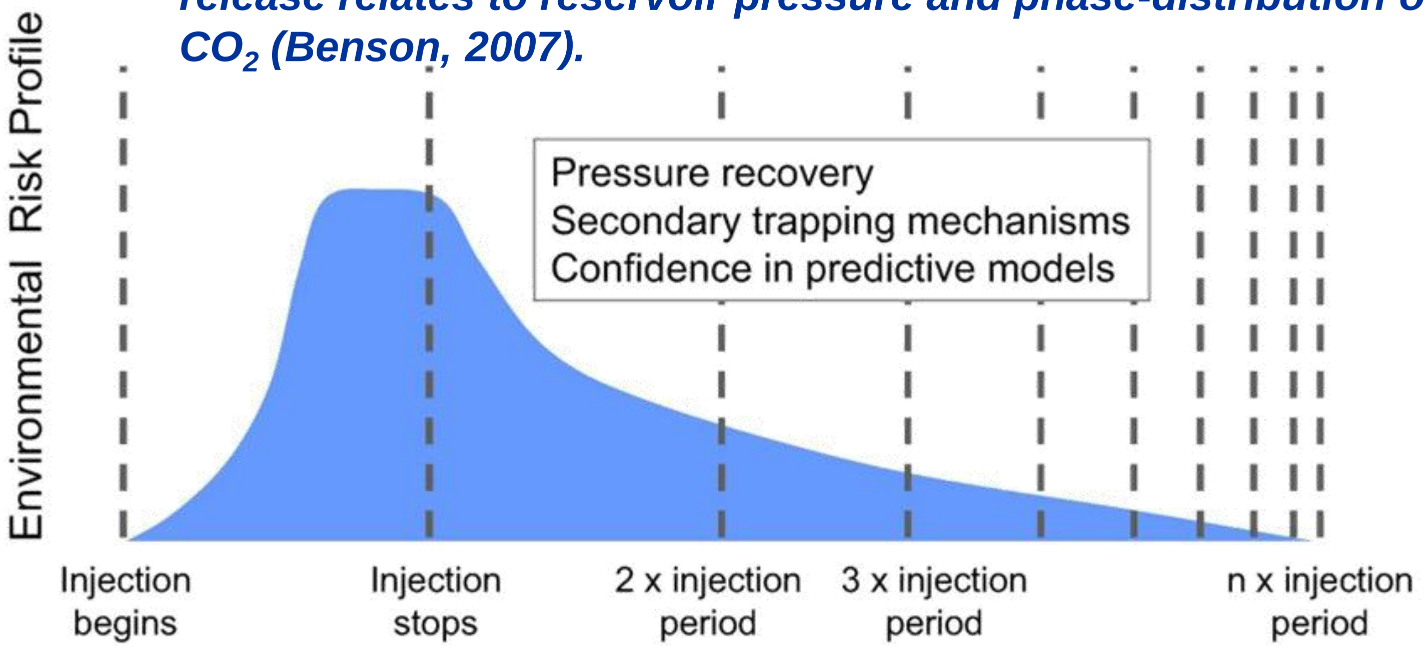
? *long-term CO_2-water-rock(-cement) reactions coupled to flow*

- *CO_2+water causes dissolution and precipitation, which changes permeability*
- *reactions in desiccating brine or supercritical CO_2*

Figures from US-DOE/NETL 2009 ("Carbon Dioxide Enhanced Oil Recovery: Untapped Domestic Energy Supply and Long Term Carbon Storage Solution")

A successful storage project will require predicting the site's performance beyond the injection phase.

Schematic description of risk assuming probability of CO_2 release relates to reservoir pressure and phase-distribution of CO_2 (Benson, 2007).



Site Characterization | **Site Operation (e.g., CO_2-EOR)** | **Post Closure** | **Long-Term Stewardship**

10^0 10^1 10^2 10^3

Time (yrs)

Risk assessment for CO_2 storage involves predicting the behavior of engineered geologic systems.

probability of an event (behavior of the system)

R = P(event) x C(event)

consequence of an event (e.g., loss resulting from event)

- **Risk assessment can address multiple factors related to CCS projects**
  - health/safety/environment concerns
  - storage project economics
  - long-term effectiveness (e.g., C credits)
- **Risk assessment can span from qualitative to quantitative**
  - FEP analysis (Features, Events, Processes)
  - process/reservoir models (detailed physics and chemistry)
  - system models
- **Natural systems are inherently heterogeneous and complex**
  - Predictions, therefore, contain uncertainty that must be addressed stochastically
- **A strong science base is essential**
  - projections must be over long time periods
  - sites will have wide variation in conditions

Potential risk-related scenarios that could impact the success of a CCS project include…

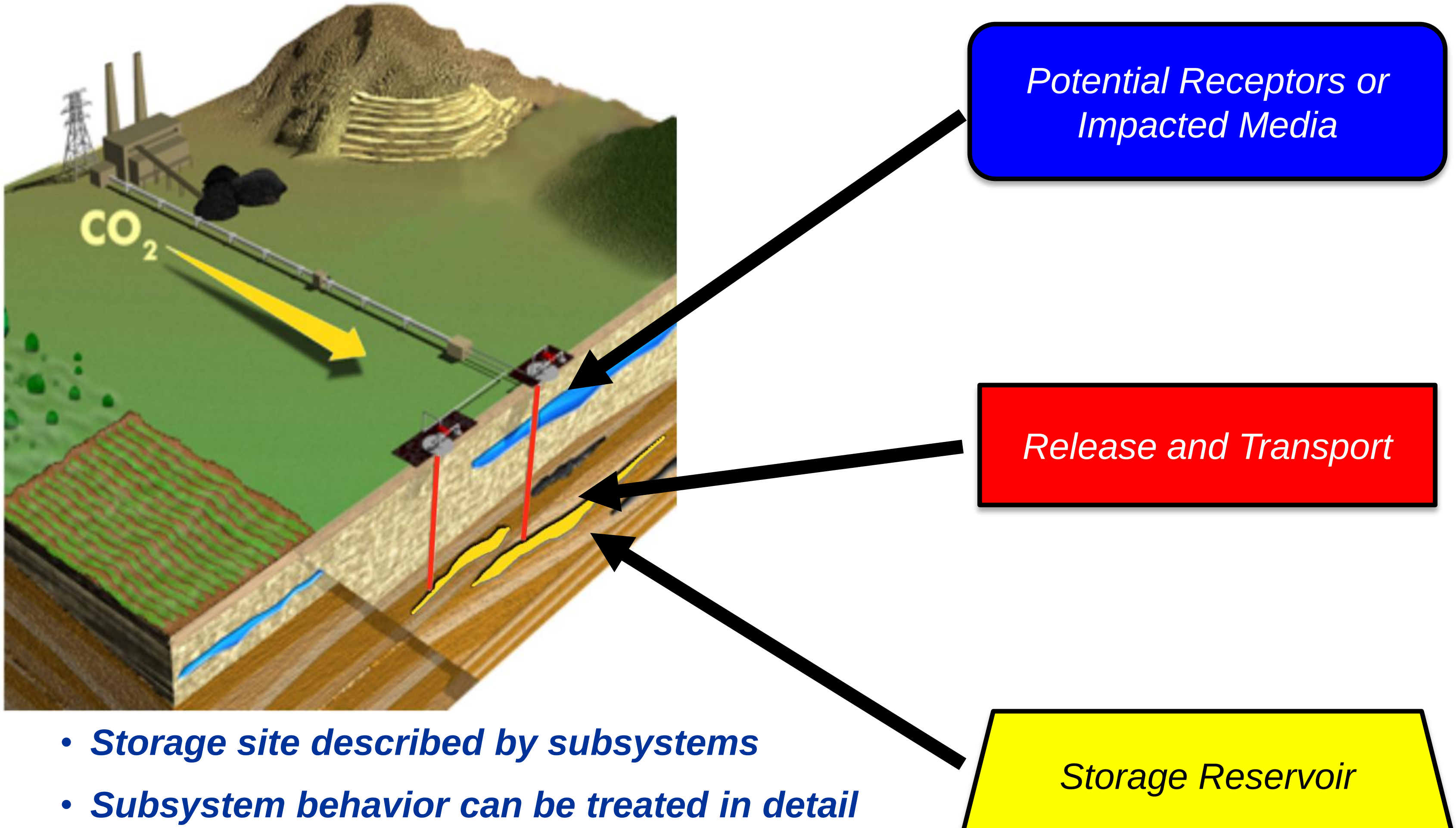
- *insufficient capacity/injectivity over time at a site*
- *impingement on pore space not covered under deed or agreement*
- *impingement on other subsurface resources*
- *change in local subsurface stress fields & geomechanical properties*
- *impact on the groundwater and/or surface water*
- *elevated soil-gas CO_2 in terrestrial ecosystems*
- *accumulation in poorly ventilated spaces or in low lying areas subject to poor atmospheric circulation*
- *CO_2 or other displaced gases (e.g., CH_4) return to the atmosphere*

➢ *Importance of direct impacts from CO_2 vs. indirect impacts (e.g., brines, pressure fronts)*

➢ *Importance of global impacts (e.g., return of CO_2 to atmosphere) vs. local/regional impacts*

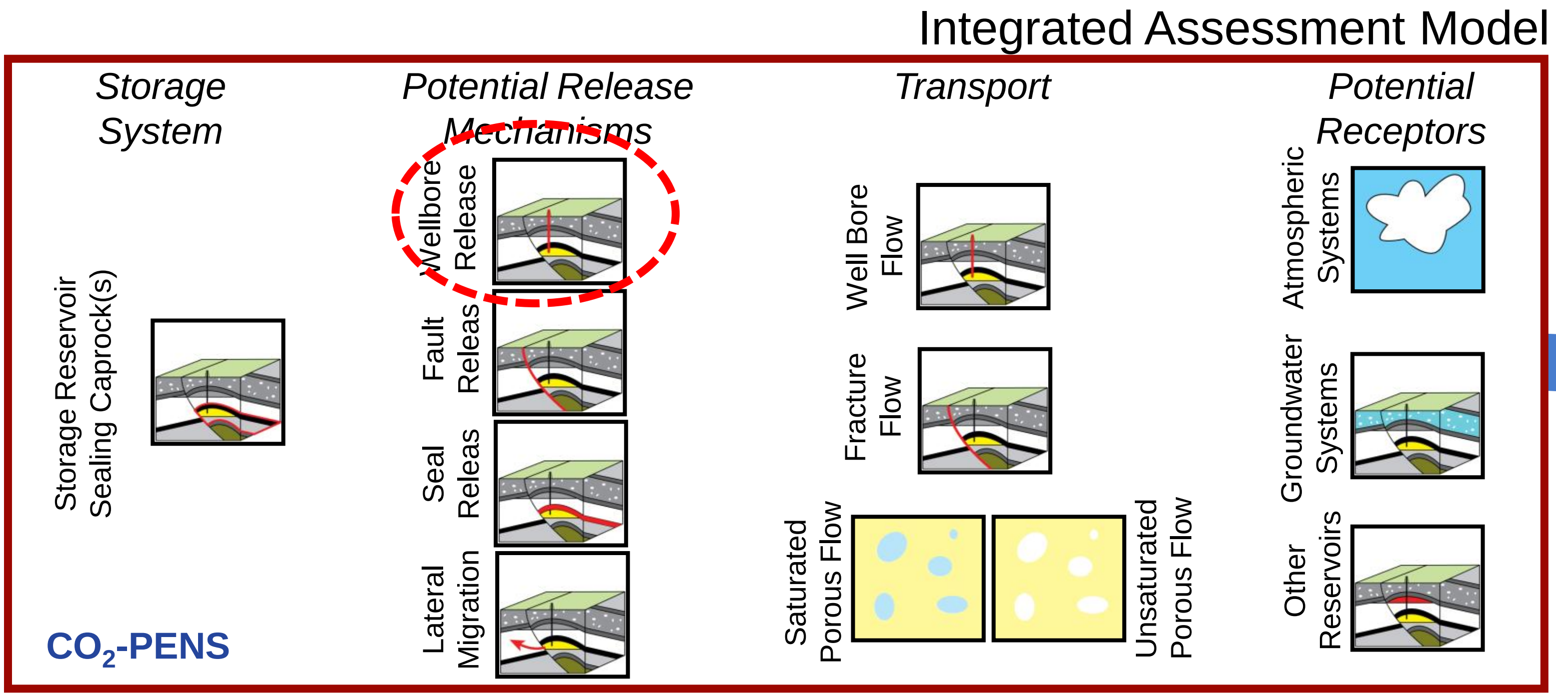
** from Carbon Sequestration Leadership Forum Task Force report*

Integrated Assessment Model Approach for Storage Site

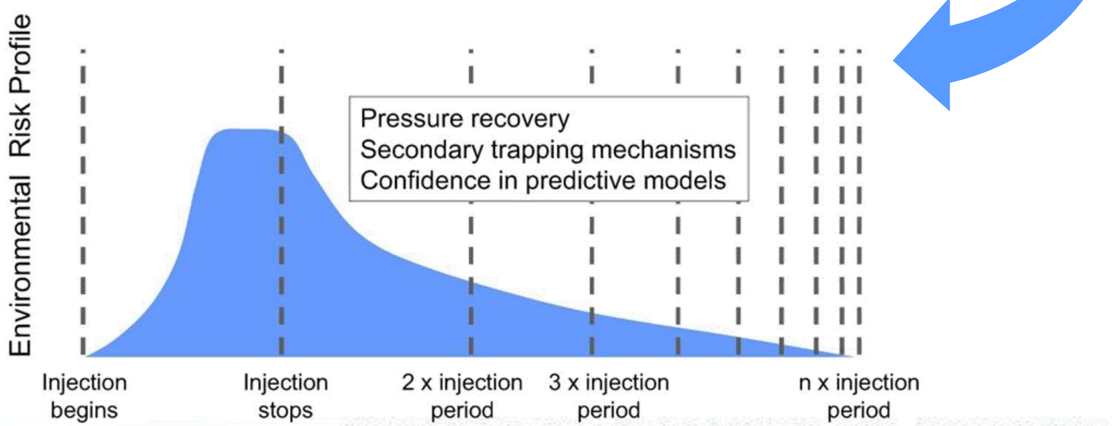


- ***Storage site described by subsystems***
- ***Subsystem behavior can be treated in detail***
- ***Uncertainty/heterogeneity handled by stochastic descriptions of subsystems***

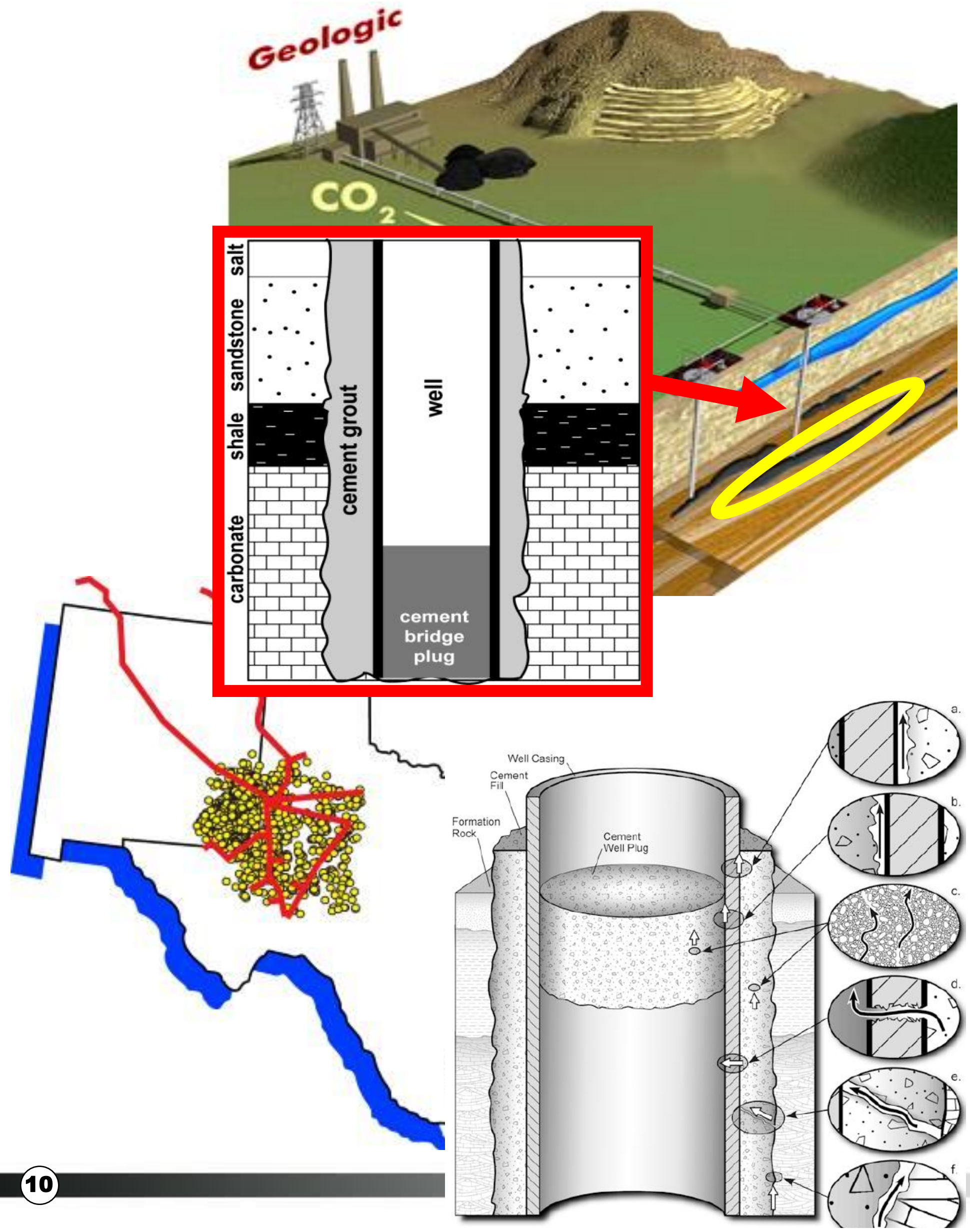
NRAP is exploring the quantification of risk profiles with process–system models to predict site performance.



Viswanathan et al., 2008; Stauffer et al., 2008



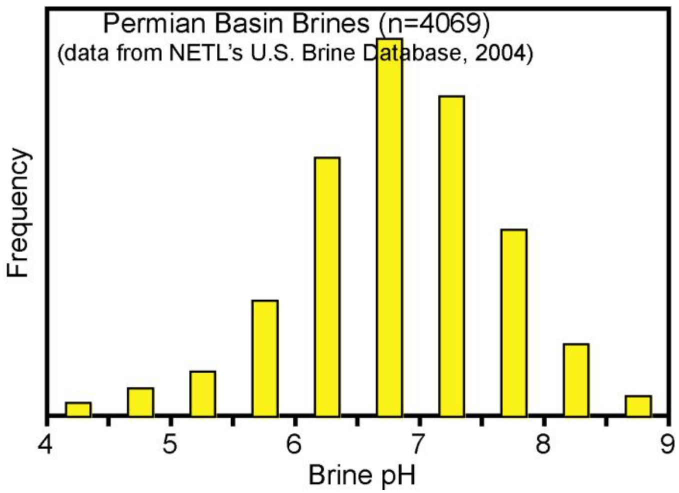
Wellbore integrity is important in long-term CO_2 storage.

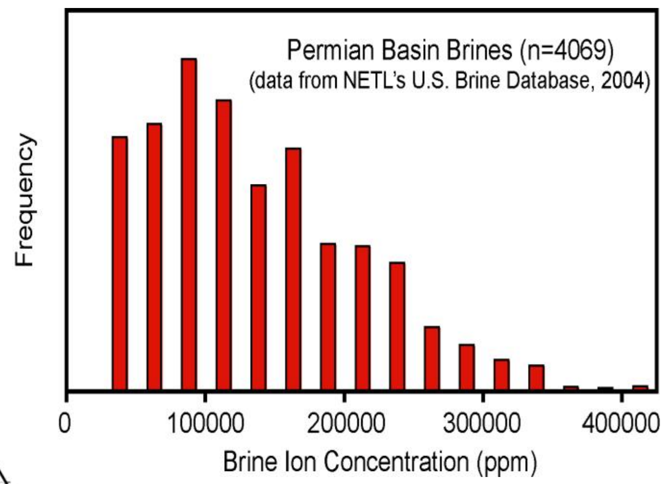


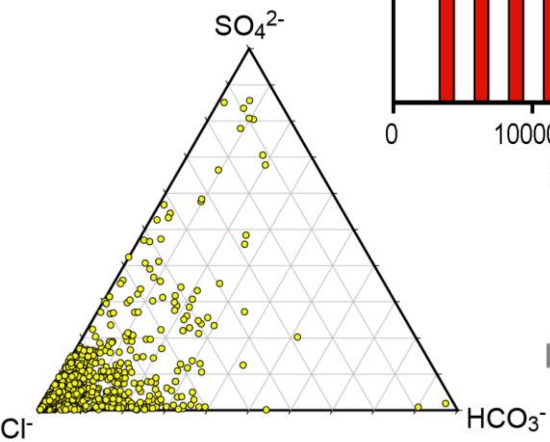
potential failure pathways (Gasda et al. 2004)

- **Wellbores are key components of a storage system and impact CO_2 fate**
  - Placement of CO_2
  - Potential release pathway from reservoir (penetration through primary seal)
  - Potential conduits/fastpaths for CO_2 movement within the geologic site
- **Wellbore integrity may be compromised in several scenarios**
  - no completion
  - poor completion or abandonment
  - mechanical damage
  - chemical damage (corrosion)
- **At system level, one can quantify aggregate rates using analogs**
  - Surface casing vent flow (Watson & Bachu, 2007, 2008)
  - Blowouts (Jordan & Benson, 2008)

Prediction of wellbore permeability is complex:
Numerous variables can impact chemical & mechanical processes.

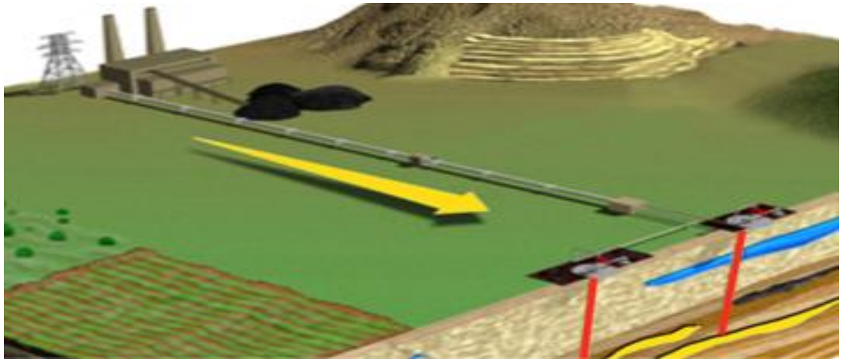






- **Hydration State of Cement (porosity, permeability, mineralogy)**
  - "slurry" characteristics (cement type; admixtures; fluids; water:cement ratio; drilling muds)
  - hydration conditions (reservoir fluids; *P*, *T*, time)
- **Chemical/Biological State of Wellbore System**
  - hydrated cement properties
  - fluid/brine chemistry (P_{CO2}, T)
  - sulfur cycle?
  - redox conditions
  - biological role?
- **Physical State of Wellbore System**
  - fractures and other flow pathways
  - effective permeability of wellbore system

Science base can enable a more reliable assessment of impact from critical processes at the system level.



wellbores permeability will increase

wellbore permeability will not increase

?

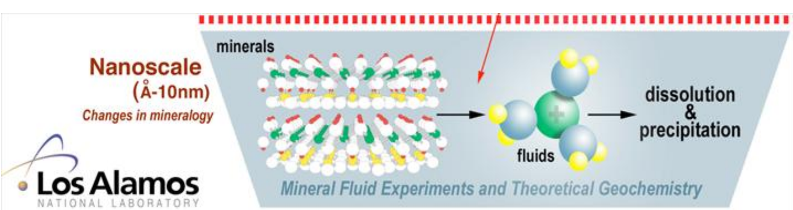
CO_2+brine dissolves hydrated cement

Based on conservative assumptions…

- *Avoid areas with wellbores*
  - *avoid depleted oil and gas reservoirs*
- *Require use of CO_2-resistant cement*
  - *higher costs & limited field-use experience*

Based on optimistic assumptions…

- *Potentially underestimate long-term costs*
  - *liability; wellbore maintenance; etc.*



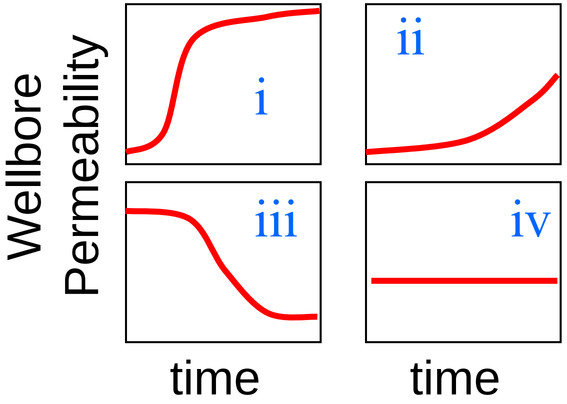
For predicting movement of CO_2 in wellbore at the system level, one must know wellbore permeability over time.

Assume that wellbore flow can be represented by Darcy's law (Norbotten et al., 2005):

$$Q_\alpha = -\left(\pi\, r_{well}^2\right)\left(k_{well}\, \lambda_\alpha\right) \frac{p_{upper} - p_{lower}}{D} \left(\rho_\alpha\, g\right)$$

Possible scenarios for wellbore fate

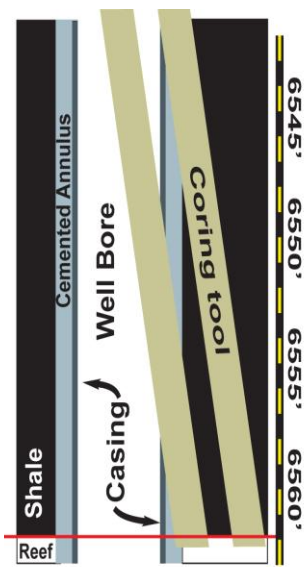
i. wellbores degrade rapidly
ii. wellbores degrade slowly
iii. wellbores improve over time
iv. wellbores are unaffected by CO_2+brine

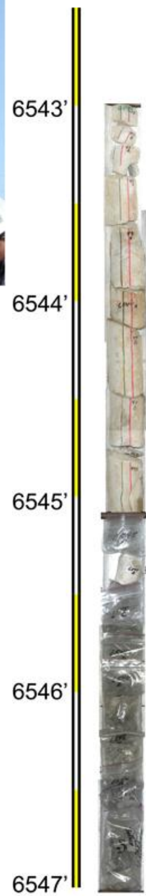


Field measurements can determine permeabilities at a specific time point.

- **Crow and Carey (2008) found effective wellbore permeabilities for a CO_2-exposed wellbore of 0.5–20 μD based on a vertical interference test.**
- **How might permeability change over time?**

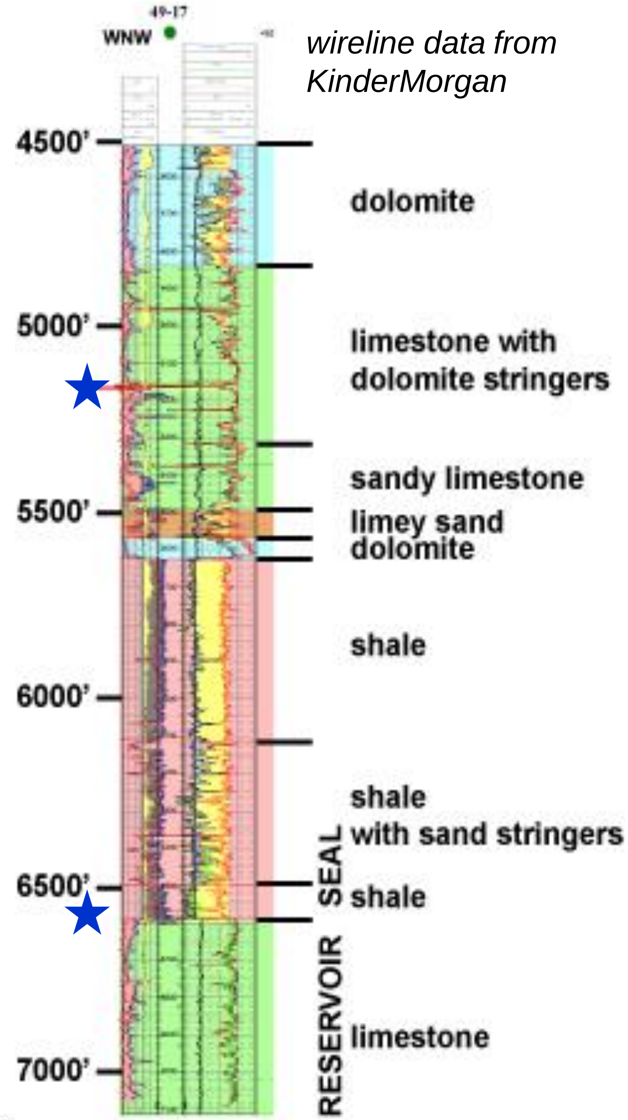
Whipstock drilling at SACROC 49-6 provided recovery of core through cemented annulus to within 7' of top of pay.





- Drilled/completed 1950
  - water used as drilling fluid
  - portland cement
- Water flood initiated 1954
  - Colorado River source supplemented by effluent
- First direct CO_2 exposure 1975
  - 10 yrs as injector; 7 yrs as producer
  - 2.2 Bscf CO_2 produced/injected
- Primary core taken at ~6550'
  - within ~7–19' from top of pay
- Additional core taken at 5160'

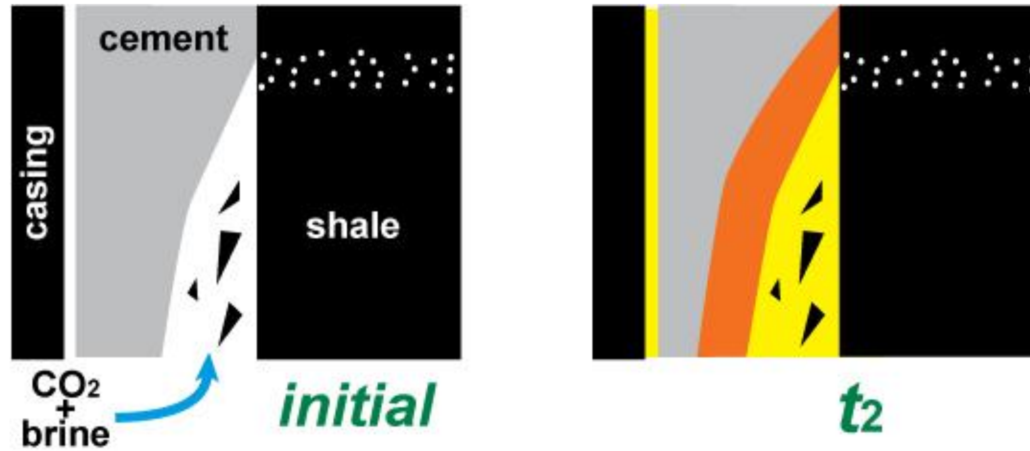
wireline data from KinderMorgan

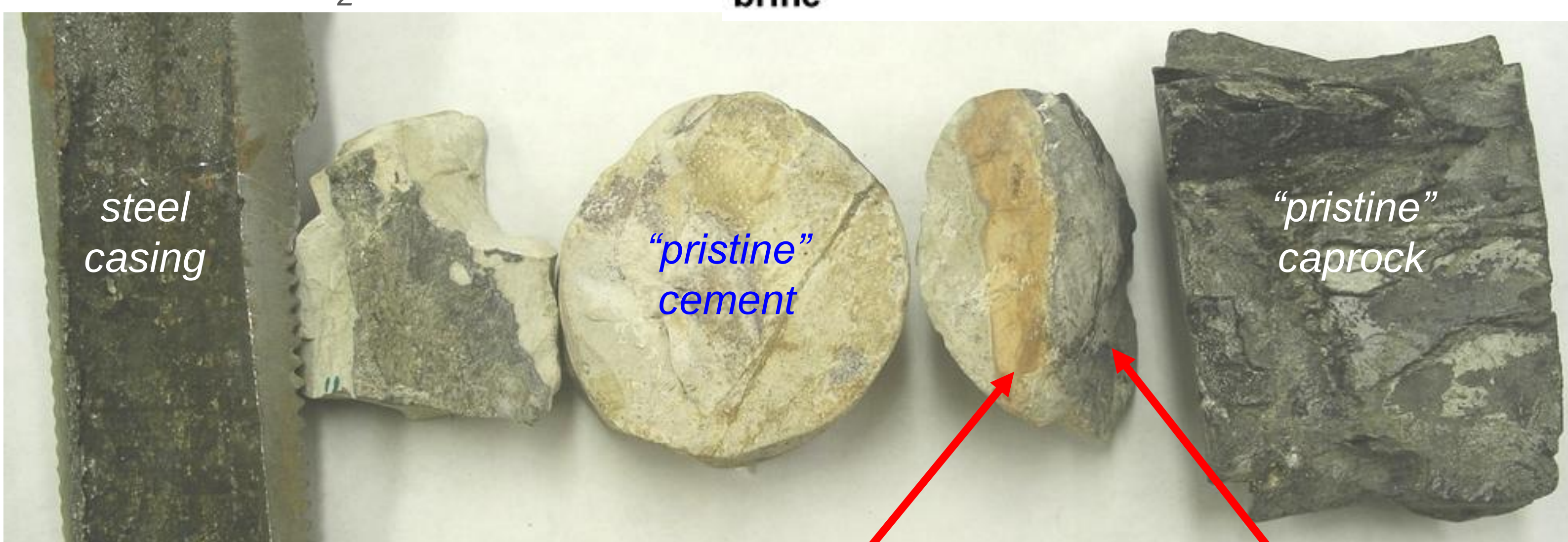


Carey et al., 2005, *SPE*;
Guthrie et al., 2005, Midland CO_2 Conf.

Field observations suggest wellbore integrity requires understanding both diffusive and advective processes.

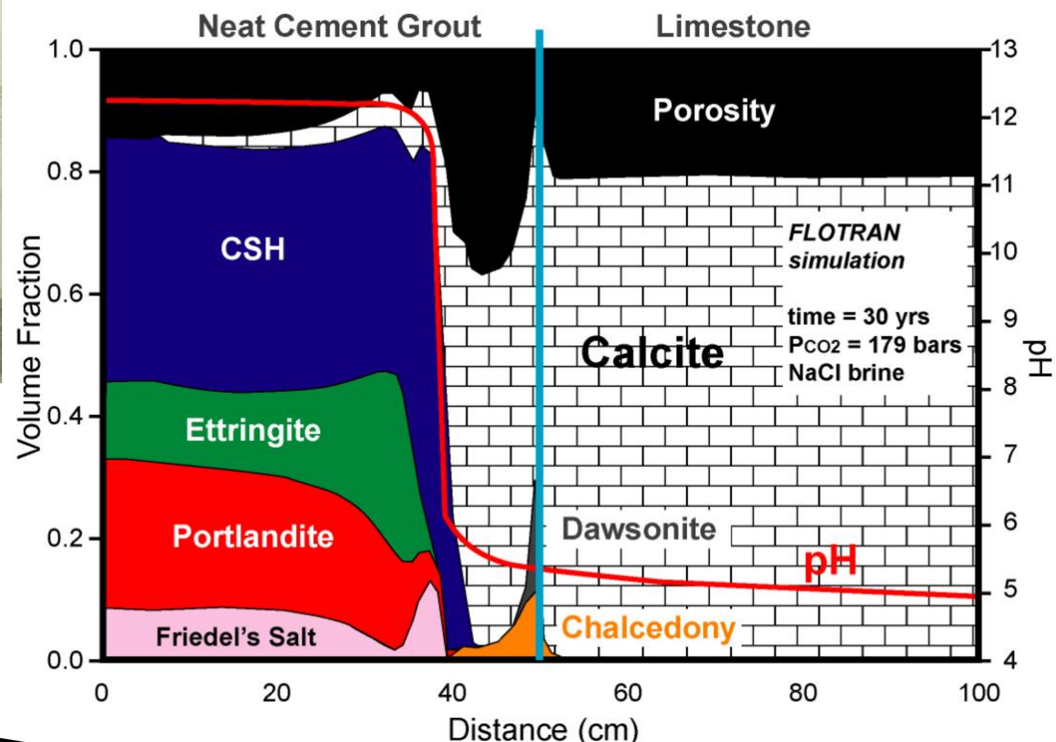
- *fluid flow along interface into sandy unit in shale*
- *precipitation of silica + carbonate from brine along interfacial zones*
- *diffusive carbonation of cement to form orange "popcorn" zone*
- *no evidence of CO_2 above seal*





Guthrie et al., 2005, Midland CO_2 Conf.; Carey et al., 2007, Int. J. GHG Control

Diffusive alteration under these conditions may result in a slight increase in permeability over time.



"Relative" Permeability
(mD; air dried)
(B. Svec, NMT)

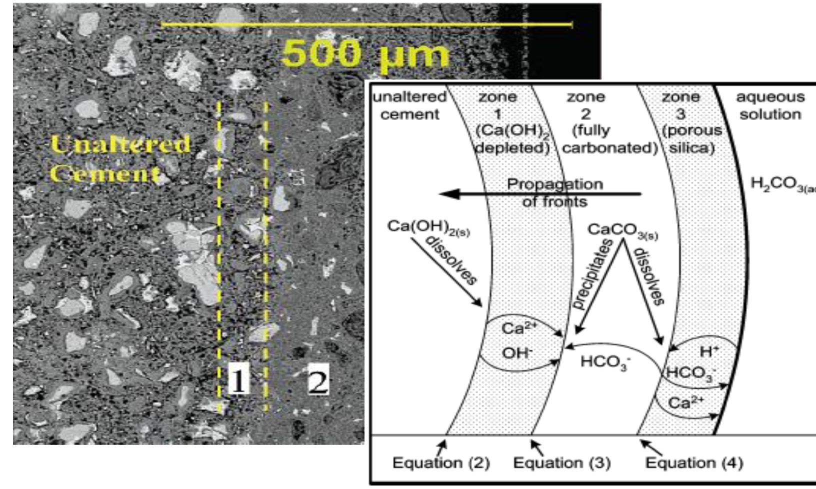
Pristine Cement (~5160')	0.09
Pristine Cement (~6550')	0.09 0.02
Altered Cement (Orange Zone) (~6550')	0.23 0.14

Carey et al., 2007, Int. J. GHG Control, 1:75-85
Lichtner & Carey, 2006, GCA, 70:1356-1378.

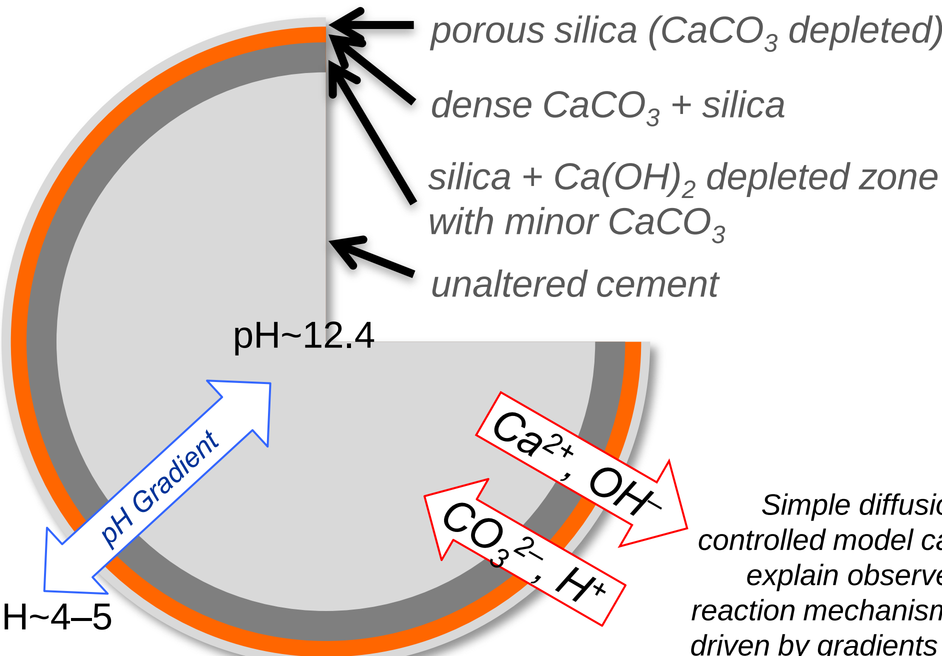
Validated experimental model (mechanisms/textures) is being used to explore other storage-reservoir conditions.

Research Status

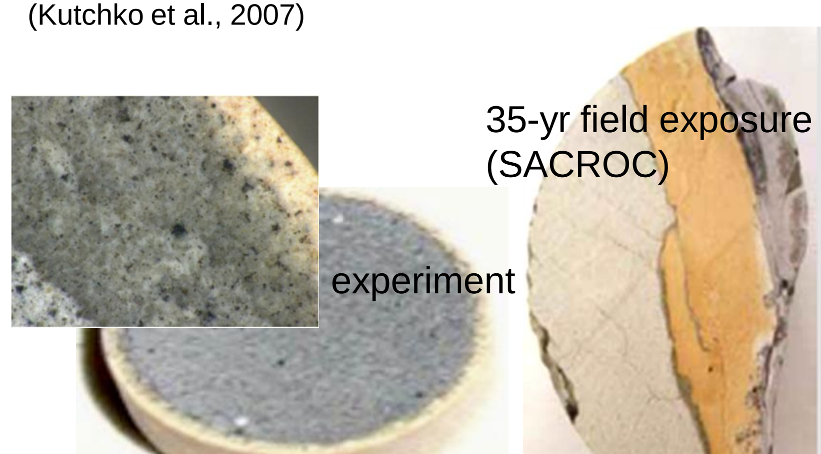
- Developed experimental model that accurately mimics field-scale processes
- Determining diffusion-controlled alteration for a variety of field conditions
  - –brine compositions; cement admixtures; water-saturated supercritical CO_2



Appropriate curing is key to accurate representation of mineralogical, chemical, and structural changes to cement (Kutchko et al., 2007)



Simple diffusion controlled model can explain observed reaction mechanisms driven by gradients in chemistry and pH

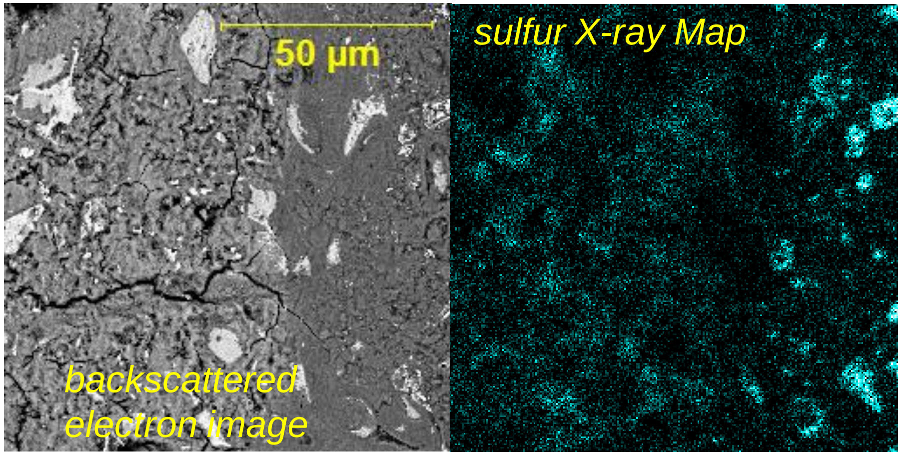


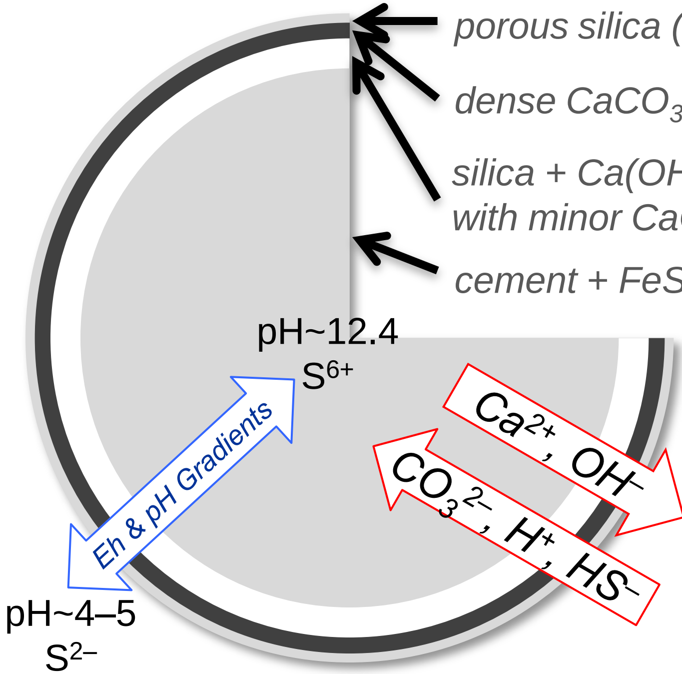
Experimental model developed so that reactions match field observations from mature EOR site (SACROC) (Kutchko et al., 2007; Guthrie et al., 2005)

Experimental model is extended to elucidate the potential impact of CO_2 impurities (co-constituents) such as H_2S.

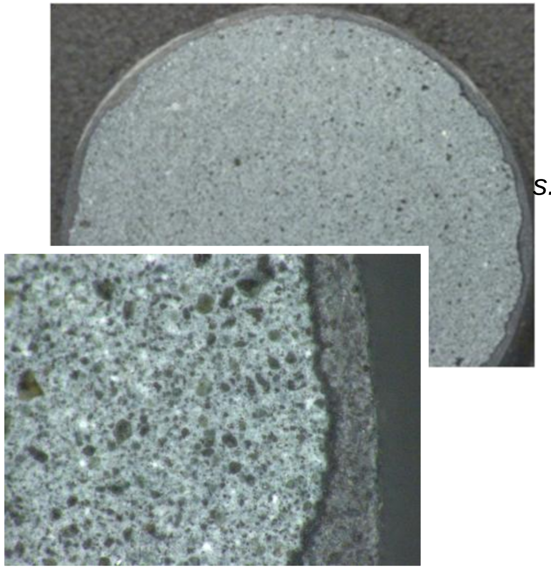
Research Status

- Determining impact of H_2S on diffusion-controlled alteration
  - –preliminary indications suggest diffusion-controlled alteration with mineralogically controlled propagation of alteration fronts



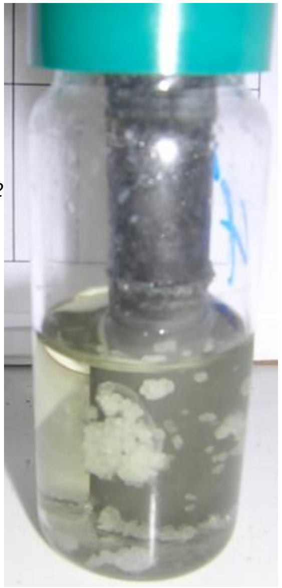


Will a simple diffusion controlled model explain observed reaction mechanisms driven by gradients in chemistry, pH, Eh



s.c. CO_2 + H_2S

CO_2 + H_2S + brine

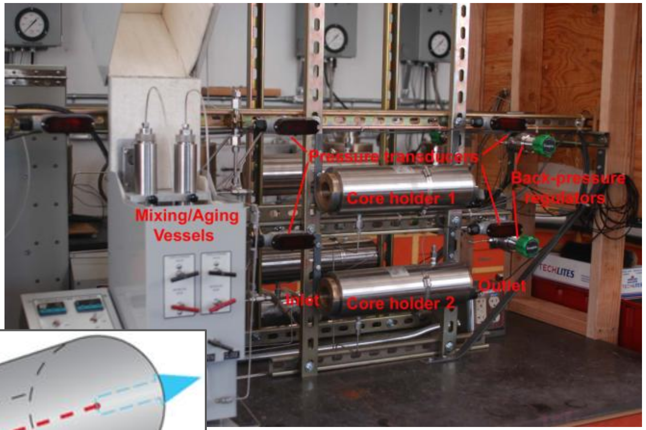


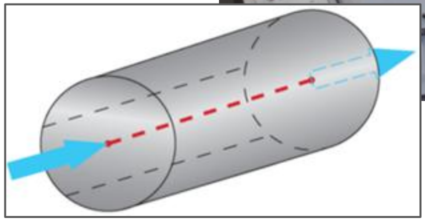
(Kutchko, Strazisar, Hwathorne, et al., in prep)

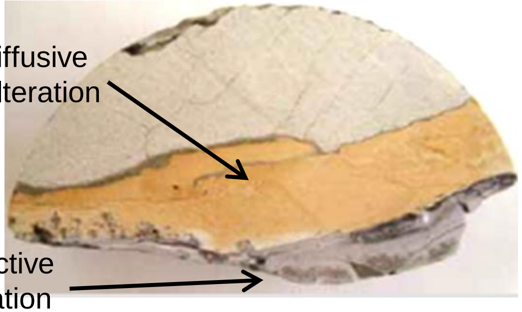
Flow-through experiments are being used to characterize evolution of open flow paths.

Research Status

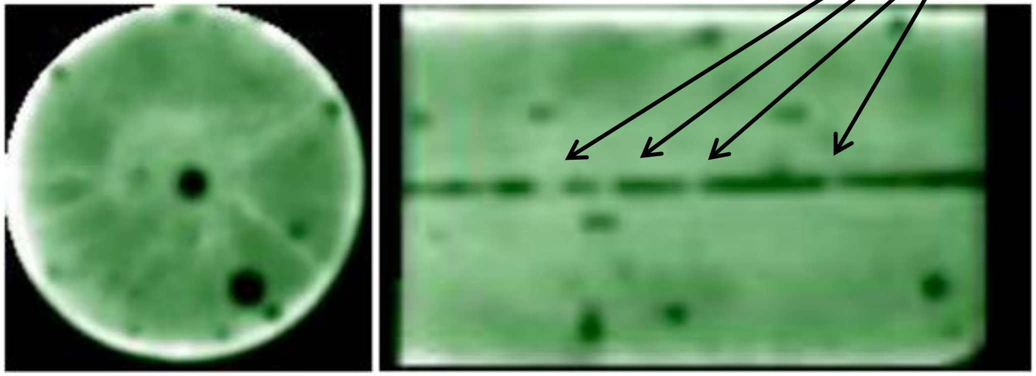
- Determining advection-controlled alteration
  - Experimental investigation of dissolution and precipitation along a flow pathway at PT is being used to baseline predictive simulations







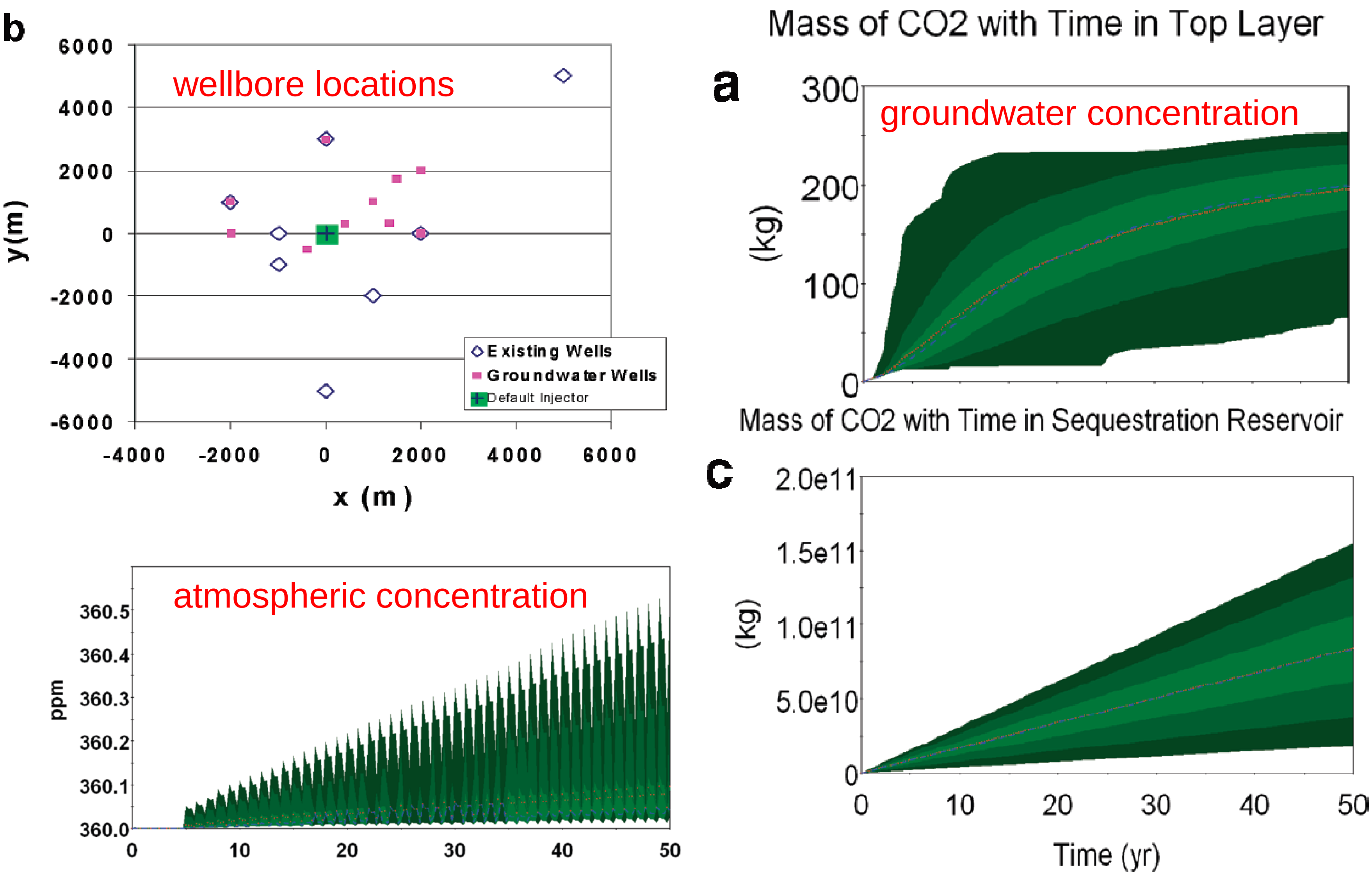
Field evidence suggests wellbore integrity can be controlled by both diffusive and advective processes. (Carey, et al. 2007)



CT images of cement core show bridging of internal flow pathway during experiment due to dissolution, transport, and precipitation in a CO_2 saturated brine.

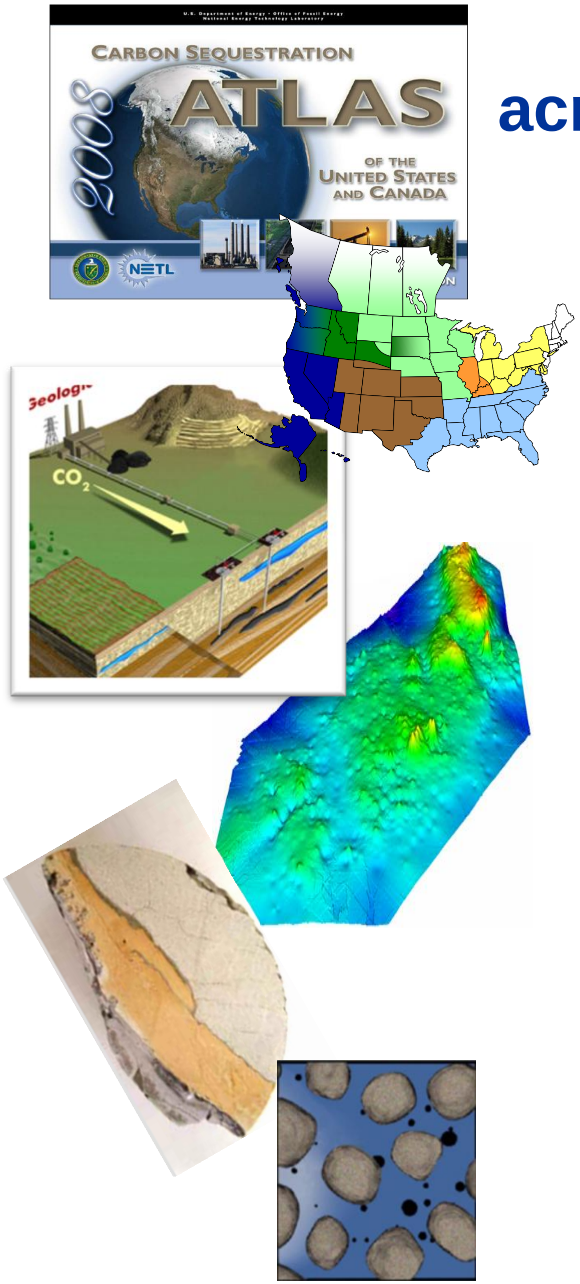
(Huerta, Strazisar, Bryant, et al., in prep)

Application of CO_2-PENS to Assessment of Potential Release:
Monitoring strategies can be tailored to likely impact scenarios.



Viswanathan et al. (2008)

NRAP research efforts are coordinated across several interdependent topical areas.



Wellbore integrity & natural-seal integrity

- open/close conditions of pathways; effective permeability
- methods to identify potential pathways

goal: quantitative estimate of potential release

Strategic monitoring

- optimization tied to risk assessment
- dynamic integration of monitoring and prediction
- quantification of reservoir stress

goal: risk-based monitoring protocol

Ensuring protection of groundwater

- comprehensive assessment of potential impacts (CO_2/O_2/…)
- identification of early signals for strategic monitoring

goal: ensure protection by early detection

Systems Modeling for Risk Assessment

- science-based site-specific risk profiles;

goal: validated, methodology for calculating risk profiles